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Nonlinear Joint Fusion and Detection of Mines Using Multisensor Data

by Nasser M. Nasrabadi

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Nasser M. Nasrabadi
Sensors and Electron Devices Directorate, ARL

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<p>This report describes a new nonlinear joint fusion and anomaly detection technique for mine detection applications using two different types of sensor data (synthetic aperture radar [SAR] and hyperspectral sensor [HS] data). A well-known anomaly detector called the “RX algorithm” is first extended to perform fusion and detection simultaneously at the pixel level by appropriately concatenating the information from the two sensors. This approach is then extended to its nonlinear version. The nonlinear fusion-detection approach is based on the statistical kernel learning theory which explicitly exploits the higher-order dependencies (nonlinear relationships) between the two types of sensor data through an appropriate kernel. Experimental results for detecting anomalies (mines) in hyperspectral imagery are presented for linear and nonlinear joint fusion and detection for a co-registered SAR and HS imagery. The results show that the nonlinear techniques outperform linear versions.</p>				
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1. Objective

The recent availability of accurately geo-located, multisensor data (collected as part of the Wide Area Airborne Mine Detection program) has created unprecedented opportunities for the exploration of multisensor, target detection algorithms. Even with this high-fidelity data set, the sensor fusion task still presents many daunting challenges. The objective of this Director's Research Initiative (DRI) investigation is to develop a nonlinear joint fusion and detection technique for mine detection applications using two different types of sensor data—synthetic aperture radar SAR data and hyperspectral sensor (HS) data. A well-known anomaly detector, called the RX algorithm,¹ is extended to perform fusion and detection simultaneously at the pixel level by appropriately concatenating the information from the two sensors. This approach is then extended to its nonlinear version. The nonlinear fusion-detection approach is based on the statistical kernel learning theory which explicitly exploits the higher-order dependencies (nonlinear relationships) between the two types of sensor data through an appropriate kernel.

2. Approach

The main purpose of this DRI project is to nonlinearly fuse the information contents in HS and SAR imagery to effectively detect targets of interests (buried and surface mines). Because of the significant differences in basic physical properties and signal dimensionality between these two sensors, fusion of the raw or processed data from these sensors might mitigate the false alarm rate significantly for anomaly detection purposes. In the previous DRI project (FY05), the main focus was on co-registration of the SAR and HS image data. Individually linear and nonlinear signal detection tools for HS and SAR imagery were developed.² In this DRI report, the nonlinear joint fusion and detection technique is summarized and its detection performance on several mine imageries is reported. The proposed approach is to extend the well-known RX anomaly detector and its nonlinear version (the kernel RX algorithm³) to an integrated multiple-sensor data.

¹ Reed, S.; Yu, X. Adaptive Multiple-Band CFAR Detection of an Optical Pattern With Unknown Spectral Distribution. *IEEE Trans. on Acoustics, Speech Signal Process* **1994**, *38* (10), 1760–1770.

² Ranney, K.; Rosario, D.; Nasrabadi, N. M. *Fusion of Synthetic Aperture Radar and Hyperspectral Imagery*; DRI proposal FY05-SED-35 and the final report FY06; U.S. Army Research Laboratory: Adelphi, MD, December 1996.

³ Kwon, H.; Nasrabadi, N. Kernel Orthogonal Subspace Projection for Hyperspectral Signal Classification. *IEEE Transactions on Geoscience and Remote Sensing* **2005**, *43* (12), 2952–2962.

2.1 Joint Fusion and Detection Using SAR and HS at the Pixel Level

In the proposed approach, detection and fusion is done at the pixel level by concatenating each HS spectral pixel with its corresponding high-resolution SAR pixels and then processing the concatenated data by the RX anomaly detector. This approach jointly exploits the linear correlation or dependencies between the two sensors in order to simultaneously fuse and detect the objects of interest. In Reed and Yu,¹ a spectral anomaly detection algorithm was developed for detecting targets of unknown spectral distribution against a background with unknown spectral covariance. This algorithm is now commonly referred to as the RX anomaly detector, which has been successfully applied to many hyperspectral target detection applications. It is now considered as the benchmark anomaly detection algorithm for multispectral/hyperspectral data. The RX algorithm is a constant false alarm rate (CFAR) adaptive anomaly detector which is derived from the Generalized Likelihood Ratio Test. The RX algorithm is based on exploiting the difference between the spectral signatures of an input pixel with its surrounding neighbors. This distance comparison is very similar to the Mahalanobis distance measure calculated by comparing the corresponding wavelengths (spectral bands) of two measurements. The RX algorithm assumes that the covariance of the background clutter is unknown or calculated from the data. In the conventional RX algorithm, a nonstationary local mean is subtracted from each spectral pixel. The local mean μ_b is obtained by sliding a double concentric window (a small inner window region [IWR] centered within a larger outer window region [OWR]; see figure 1) over every spectral pixel in the image and calculating the mean of the spectral pixels falling within the outer window. The size of the inner window is assumed to be the size of the typical target of interest in the image. The residual signal after mean subtraction is assumed to approximate a zero-mean pixel-to-pixel independent Gaussian random process. Let each input spectral signal consisting of J spectral bands be denoted by $x(n) = (x_1(n), x_2(n), \dots, x_J(n))^T$. Define X_b to be a $J \times M$ matrix of M centered (mean-removed) reference background clutter pixels (or pixels in the outer window). Each observation spectral pixel is represented as a column in the sample matrix $X_b = [x(1), x(2), \dots, x(M)]$.

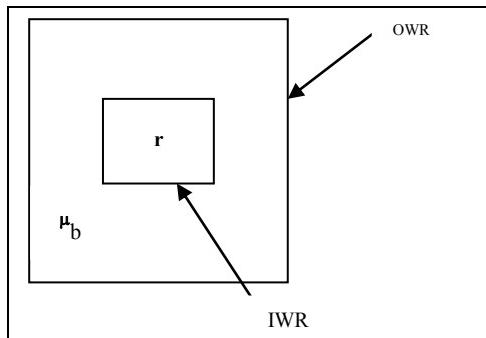


Figure 1. A sliding dual window: an IWR and an OWR.

Consider a test pixel r_{ij} at pixel location (i, j) . The RX algorithm output at each pixel is given by the following:

$$\delta_{rx}(r_{ij}) = (r_{ij} - \hat{\mu}_b)^T \hat{C}_b^{-1} (r_{ij} - \hat{\mu}_b), \quad (1)$$

where r_{ij} represents the pixel under consideration located at the center of the IWR, $\hat{\mu}_b$ represents the estimated mean of the pixels within the OWR, and \hat{C} is the estimated covariance matrix of the pixels within the OWR given by $\hat{C} = (1/N) \mathbf{X}_b \mathbf{X}_b^T$.

The size of the dual window is set such that the IWR encloses a target-sized region and the OWR includes its surrounding region. If the dual window is placed within a spatially homogeneous region consisting of similar types of materials, such as natural backgrounds, the statistical characteristics of the IWR and OWR will be similar to each other. The IWR and OWR will contain significantly different statistical features if the dual window is centered on a region where the target is surrounded by the local background. Use of appropriate thresholding on the RX output (equation 1) allows most targets to be detected as anomalies.

The dual window RX algorithm (equation 1) is easily applied to each HS pixel since these pixels are already in vector form. However, in the case of high resolution SAR each co-registered HS pixel corresponds to a block of pixels in the SAR image due to the difference in spatial resolution between the SAR and HS. For SAR imagery we group all the pixels that physically correspond to a single HS pixel and represent them as a SAR vector pixel. This process is done for each corresponding HS pixel in order to form a SAR cube image of the same spatial resolution as HS image. It should be noted that the number of corresponding SAR pixels to each HS pixel will obviously be different from the number of spectral bands in HS. Now the RX-algorithm can be applied separately to the HS and SAR cubes of the same resolution to obtain the anomalies from each sensor data.

To develop an RX-like joint fusion and anomaly detection algorithm, let each pixel located at (i, j) in the HS image be represented by a vector $\mathbf{x}_h(i, j)$ consisting of J spectral bands and the corresponding block of pixels centered at (i, j) be represented by $\mathbf{x}_s(i, j)$ consisting of P pixels since for practical platforms, the SAR image has much higher resolution than the HS sensor. Furthermore, let the concatenated vectors from the two sensors corresponding to the same HS pixel location (i, j) after normalization be represented by a partition vector $\mathbf{x}_{hs}(i, j) =$

$$\begin{bmatrix} \mathbf{x}_h(i, j) \\ \mathbf{x}_s(i, j) \end{bmatrix}$$
, where $\mathbf{x}_h(i, j)$ and $\mathbf{x}_s(i, j)$ are the pixels under consideration at the center of the dual

window in the HS and SAR images, respectively. Applying the RX algorithm on the concatenated data $\mathbf{x}_{hs}(i, j)$ is given by the following:

$$\delta_{\text{rx}}^{\text{hs}}(i,j) = \left(\begin{bmatrix} \mathbf{x}_h(i,j) \\ \mathbf{x}_s(i,j) \end{bmatrix} - \begin{bmatrix} \hat{\mu}_h \\ \hat{\mu}_s \end{bmatrix} \right)^T \begin{pmatrix} \hat{\mathbf{C}}_{hh} & \hat{\mathbf{C}}_{hs} \\ \hat{\mathbf{C}}_{sh} & \hat{\mathbf{C}}_{ss} \end{pmatrix}^{-1} \left(\begin{bmatrix} \mathbf{x}_h(i,j) \\ \mathbf{x}_s(i,j) \end{bmatrix} - \begin{bmatrix} \hat{\mu}_h \\ \hat{\mu}_s \end{bmatrix} \right), \quad (2)$$

where $\hat{\mu}_h$ and $\hat{\mu}_s$ are the estimated means of all the pixels (\mathbf{x}_h and \mathbf{x}_s) in the corresponding outer windows and $\hat{\mathbf{C}}_{hh}$ and $\hat{\mathbf{C}}_{ss}$ are the estimated covariance matrices of the HS and SAR data, respectively. In equation 2, the linear correlation between the HS and SAR data is exploited through the inverse covariance matrix of the concatenated data. If the SAR data is not linearly correlated to the HS data $\hat{\mathbf{C}}_{hs} = \hat{\mathbf{C}}_{ss} = 0$ in equation 2, then the joint fusion/detection algorithm is the same as performing the RX on each sensor data separately and adding the results.

2.2 Nonlinear Joint Fusion and Detection Using SAR and HS at the Pixel Level

One way to exploit the higher-order correlation between the two data is to *explicitly* map each sensor data into a higher dimension by a nonlinear mapping. For example, assume the input hyperspectral data is represented by the data space ($\mathcal{X} \subseteq \mathbf{R}^d$) and \mathcal{F} is a feature space associated with \mathcal{X} by a nonlinear mapping function.

$$\begin{aligned} \Phi: \mathcal{X} &\rightarrow \mathcal{F} \\ \mathbf{x}_h(i,j) &\mapsto \Phi(\mathbf{x}_h(i,j)), \end{aligned} \quad (3)$$

where $\mathbf{x}_h(i,j)$ is an input vector which is mapped into a potentially much higher (possibly infinite) dimensional feature space. Any linear anomaly technique can now be remodeled into this high-dimensional feature space by replacing the original input data $\mathbf{x}_h(i,j)$ with the mapped data $\Phi(\mathbf{x}_h(i,j)) = \mathbf{x}_{\phi}^h(i,j)$. Due to the high dimensionality of the feature space, \mathcal{F} , it is computationally not feasible to directly implement any algorithm in this feature space. However, kernel-based learning techniques use an effective kernel trick given by the following:

$$k(\mathbf{x}, \mathbf{y}) = \langle \Phi(\mathbf{x}), \Phi(\mathbf{y}) \rangle = \Phi(\mathbf{x})^T \Phi(\mathbf{y}), \quad (4)$$

which implements a dot product between two vectors in the feature space by employing a kernel function k associated with the nonlinear mapping Φ . Using the kernel trick representation (equation 4), allows us to implicitly compute the dot products in \mathcal{F} without mapping the input vectors into \mathcal{F} . Therefore, in the kernel methods, the mapping function, Φ , does not have to be identified. A dot product in \mathcal{F} can be avoided and replaced by a kernel function, k , a nonlinear function which can be easily calculated without identifying the nonlinear map, Φ .

A preferred kernel to utilize is the Gaussian radial basis function kernel:

$$k(\mathbf{x}, \mathbf{y}) = \exp\left(-\frac{\|\mathbf{x} - \mathbf{y}\|^2}{\sigma}\right), \text{ where } \sigma > 0 \text{ is a constant.}$$

Kwon and Nasrabadi³ show how to extend the RX algorithm given by equations 1 or 2 to a nonlinear version (so-called kernel RX) by using the idea of kernel-based learning theory. The kernel version of the linear RX algorithm³ for HS and SAR sensor data is given by equations 5 and 6, respectively.

$$\delta_{\text{KRX}}^h(i, j) = (\mathbf{k}_{x_h} - \mathbf{k}_{\mu_h})^T \mathbf{K}_{x_{hh}}^{-2} (\mathbf{k}_{x_h} - \mathbf{k}_{\mu_h}), \quad (5)$$

and

$$\delta_{\text{KRX}}^s(i, j) = (\mathbf{k}_{x_s} - \mathbf{k}_{\mu_s})^T \hat{\mathbf{K}}_{x_{ss}}^{-2} (\mathbf{k}_{x_s} - \mathbf{k}_{\mu_s}), \quad (6)$$

where $\mathbf{k}_{x_h} = k(\mathbf{X}_h, \mathbf{x}_h(i, j))$, $\mathbf{k}_{x_s} = k(\mathbf{X}_s, \mathbf{x}_s(i, j))$, $\mathbf{k}_{\mu_h} = k(\mathbf{X}_h, \mu_h(i, j))$, and $\mathbf{k}_{\mu_s} = k(\mathbf{X}_s, \mu_s(i, j))$ are the kernel empirical expansion maps and similarly, $\mathbf{K}_{x_{hh}} = \mathbf{K}(\mathbf{X}_h, \mathbf{X}_h) = (\mathbf{K})_{ij}$ and $\mathbf{K}_{x_{ss}} = \mathbf{K}(\mathbf{X}_s, \mathbf{X}_s) = (\mathbf{K})_{ij}$ are $N \times N$ kernel (gram) matrices whose entries are the dot products $\langle \Phi(\mathbf{x}_h(i)), \Phi(\mathbf{x}_h(j)) \rangle$ and $\langle \Phi(\mathbf{x}_s(i)), \Phi(\mathbf{x}_s(j)) \rangle$, respectively. \mathbf{X}_h and \mathbf{X}_s are matrices whose columns represent the data in the outer window of HS and SAR, respectively. The kernel RX version for the concatenated data is given by the following:

$$\delta_{\text{KRX}}^{hs}(i, j) = (\mathbf{k}_{x_{hs}} - \mathbf{k}_{\mu_{hs}})^T \mathbf{K}_{x_{hs}}^{-2} (\mathbf{k}_{x_{hs}} - \mathbf{k}_{\mu_{hs}}), \quad (7)$$

where $\mathbf{k}_{x_{hs}} = \mathbf{k}_{x_h} + \mathbf{k}_{x_s}$, $\mathbf{k}_{\mu_{hs}} = \mathbf{k}_{\mu_h} + \mathbf{k}_{\mu_s}$, and $\mathbf{K}_{x_{hs}} = \mathbf{K}_{x_{hh}} + \mathbf{K}_{x_{ss}}$, which is a $N \times N$ kernel matrix whose entries are the dot products.

$$\begin{aligned} (\mathbf{K}_{x_{hs}})_{ij} &= k(x_{hs}(i), x_{hs}(j)) = \langle \{\Phi(x_h(i)), \Phi(x_s(i))\}, \{\Phi(x_h(j)), \Phi(x_s(j))\} \rangle \\ &= \langle \{\Phi(x_h(i)), \Phi(x_h(j))\} \rangle + \langle \{\Phi(x_s(i)), \Phi(x_s(j))\} \rangle. \end{aligned} \quad (8)$$

Using different kernel functions or appropriately weighting the kernel functions for HS or SAR can achieve different fusion results.

3. Results

The hyperspectral mine image consists of 70 bands over the spectral range of 8–11.5 μm, which includes the long-wave infrared band. The SAR images used were produced from a SAR sensor operating in the high- and low-frequency range. Figure 2a and b shows the co-registered SAR and HS images, which contain surface mines and disturbed soil representing buried mines, respectively. The RX anomaly detector has been implemented, as well as the kernel RX, to detect mines in SAR and HS images separately and on concatenated SAR/HS data to obtain a

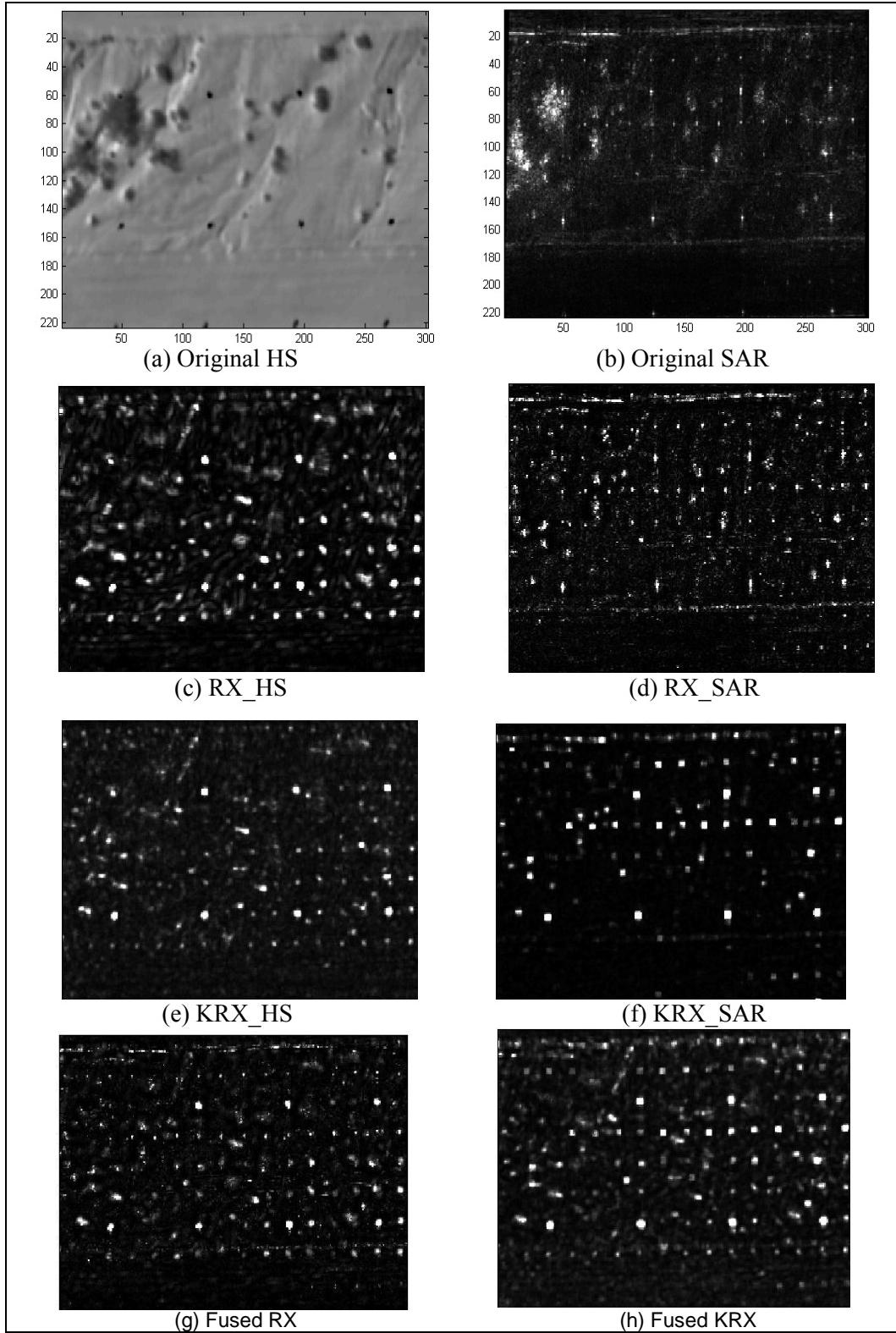


Figure 2. (a) HS image, (b) SAR image, (c) RX detected mines for HS, (d) RX detected mines for SAR, (e) kernel RX detected mines for HS, (f) kernel RX detected mines for SAR, (g) joint linear fusion/detection RX results, and (h) joint nonlinear fusion/detection KRX results.

joint fusion/detection algorithm. Figure 2a and b shows the original HS and SAR images of the same region that are processed, respectively. Results of the RX algorithm and kernel RX are shown in figure 2c–f. Figure 2g and h shows the joint linear and nonlinear fusion/detection results using the concatenated data, and the ROC curves are represented in figure 3. It is clear from figure 3 that the nonlinear joint fusion/detection algorithm performance exceeds the linear RX as well as the single sensor results.

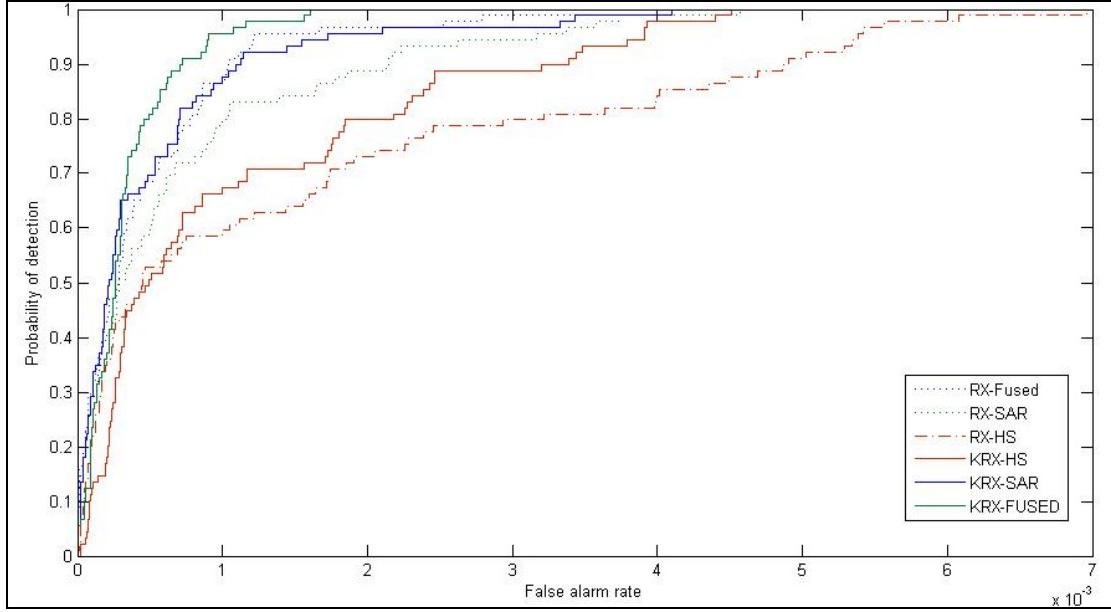


Figure 3. The ROC plots for the conventional RX and kernel RX algorithms.

4. Conclusions

A nonlinear fusion algorithm for detection of surface and buried mines has been designed. Nonlinear pixel level joint fusion and detection were developed based on the in-house kernel RX algorithm. The nonlinear correlation between the SAR and HS data was exploited in the pixel-based fusion and detection algorithm. Use of different kernels as well as developing procedures for weighting the kernels is still to be investigated.

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